The Internal Assessment of Uncertainty, CIAU and CIAU-TN: Features and Key Applications

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Abstract

The evaluation of uncertainty constitutes the necessary supplement of Best Estimate (BE) calculations performed to understand accident scenarios in water cooled nuclear reactors. The needs come from the imperfection of computational tools on the one side and from the interest in using such tool to get more precise evaluation of safety margins. In the present paper the approaches to uncertainty are outlined and the CIAU (Code with capability of Internal Assessment of Uncertainty) and CIAU-TN (its extension to 3D Thermal-hydraulics/Neutron-Kinetics couple code calculations) methods proposed by the University of Pisa (UNIPI) are described including the basic ideas and the results from key applications.

Two approaches are distinguished that are characterized as "propagation of code input uncertainty" and "propagation of code output accuracies". For both methods, the thermal-hydraulic code is at the centre of the process of uncertainty evaluation: in the former case the code itself is adopted to compute the error bands and to propagate the input errors, in the latter case the errors in code application to relevant measurements are used to derive the error bands

The CIAU (and CIAU-TN) method exploits the idea of the "status approach" for identifying the thermal-hydraulic conditions of an accident in any Nuclear Power Plant (NPP). Errors in predicting such status are derived from the comparison between predicted and measured quantities and, in the stage of the application of the method, are used to compute the uncertainty.

KEYWORDS: Uncertainty, Best-estimate, System Codes, User effect, CIAU

1. Introduction

Deterministic safety analysis frequently referred to as accident analysis is an important tool for confirming the adequacy and efficiency of provisions within the defense in depth concept for the safety of Nuclear Power Plants. Typical upgraded international licensing environments offer two acceptable options for demonstrating that the safety is ensured with sufficient margin: use of best estimate computer codes either combined with conservative input data or with realistic input data but associated with evaluation of uncertainty of results. The second option is particularly attractive because it allows for more precise specification of safety margins and their potential use for higher operational flexibility. This constitutes the framework for the present paper.

Thermal-hydraulic system codes are needed to perform deterministic safety analyses and are suitable to calculate complex accident scenarios expected in water cooled nuclear reactors. The

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outputs of those codes are affected by unavoidable errors that are referred as uncertainties, notwithstanding extensive qualification programs carried out in the last three or four decades. In the current situation it can be said that the experimental programs have not been capable to prevent those errors but to identify and to characterize them.

The present paper aims at characterizing the approaches for performing uncertainty studies and at presenting the successful uncertainty methods (CIAU and CIAU-TN) proposed by the University of Pisa.

2. The Approaches to Calculate the Uncertainty

An uncertainty analysis consists of identification and characterization of relevant input parameters (input uncertainty) as well as of the methodology to quantify the global influence of the combination of these uncertainties on selected output parameters (output uncertainty). These two main items are treated in different ways by the various methods.

One approach is to evaluate the '*propagation of input uncertainties'*, Fig. 1a: uncertainty is derived following the identification of 'uncertain' input parameters with specified ranges or/and probability distributions of these parameters, and performing calculations varying these parameters. The propagation of input uncertainties can be performed either by deterministic or by probabilistic methods. The other approach, Fig. 1b, is the '*extrapolation of output accuracies*': uncertainty is derived from the (output) uncertainty based on the comparison between calculation results and significant experimental data.

2.1 The propagation of code input uncertainty: Probabilistic Methods

The GRS is selected as the prototype method, ref. [1], for the description of the *"propagation of code input uncertainty"* approach. The probabilistic methods have the following common features:

- The nuclear power plant, the code and transient to be analyzed are identified.
- Uncertainties (plant initial and boundary conditions, fuel parameters, modelling) are identified.
- The methods restrict the number of input uncertainties to be included in the calculations. The GRS method includes all identified potentially important uncertainties.

The selected input uncertainties are ranged using relevant separate effects data. The state of knowledge of each uncertain input parameter within its range is expressed by a subjective probability distribution. The word "subjective" expresses the state of knowledge rather than stochastic variability. Dependencies between uncertain input parameters should be identified and quantified.

The typical path for uncertainty evaluation in this type of approach is depicted in Fig. 1a. The number 'n' of inputs can be as large as 10^5, whereas the dimension 'm' of outputs is not a main concern. The propagation of code input uncertainties implies that:

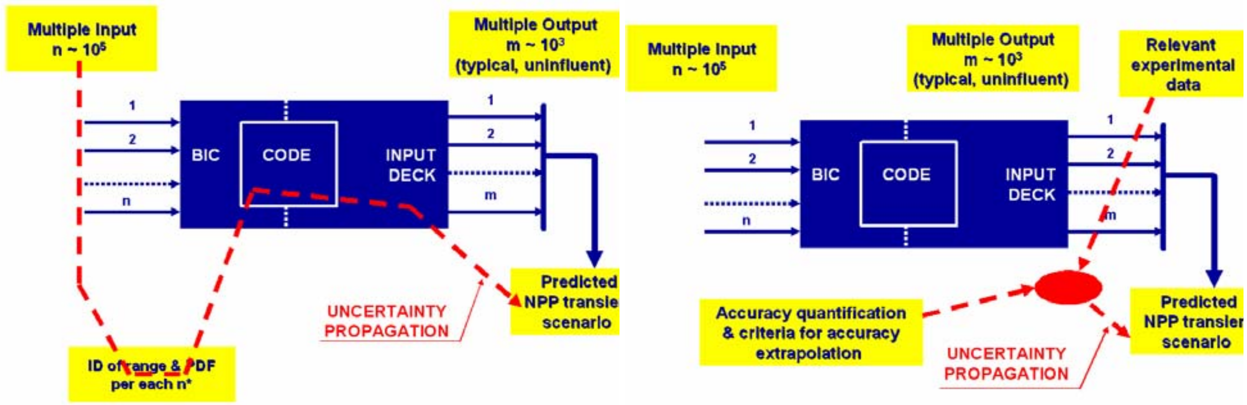
- A number 'n*' of inputs must be selected with 'n*' of the order of 10^2 and much less than 'n';
- The ranges of variations and/or Probability Distribution Function (PDF) must be assigned to each of the 'n*' parameters.

The main drawbacks of this approach are:

- Engineering judgment needed to select the dimension of 'n*' starting from 'n' and the range and/or PDF for each 'n*';
- The error propagation occurs trough the code that, by definition, is an 'imperfect' tool.

Figure 1: Classification of uncertainty methodologies.

a) Propagation of input uncertainties ***b) Propagation of output accuracies***



2.2 The propagation of code input uncertainty: Deterministic Methods

The deterministic methods have the following features in common with probabilistic methods:

- The code and nuclear power plant and transient are identified.
- Uncertainties (initial and boundary conditions, modelling, plant, fuel) are identified.

The difference to deterministic methods is in quantifying the input parameter uncertainties. No subjective probability distributions are used; instead, “reasonable” uncertainty ranges or bounding values are specified that encompass e.g. available relevant experimental data. The statements of the uncertainty of code results are deterministic, not probabilistic.

2.3 Extrapolation of output accuracies

The UMAE (Uncertainty Method based on Accuracy Extrapolation) is the prototype method, ref. [2], for the description of *“the propagation of code output accuracies”* approach. The method focuses not on the evaluation of individual parameter uncertainties but on the propagation of errors from a suitable database calculating the final uncertainty by extrapolating the accuracy from relevant integral experiments to full scale NPP The flow diagram of UMAE is given in Fig. 2. The bases of the method and the conditions to be fulfilled for its application can be found in refs. [2] to [5].

The basic idea of this approach is to get the uncertainty from considering the accuracy (i.e. discrepancy between measured and calculated value). The use of data base from counterpart and similar tests (similar tests are experiments performed in different scaled facilities that are characterized by the occurrence of the same thermal-hydraulic phenomena; counterpart tests are similar tests where boundary and initial conditions are imposed according to a scaling analysis.) in Integral Tests Facilities (ITF) is crucial for this method. The underlying assumption of this extrapolation method is that the direct extrapolation of experimental data is not acceptable for the uncertainty prediction of a nuclear power plant (NPP), but that it is reasonable to extrapolate the discrepancies between code results and experimental data observed for similar phenomena in qualified ITF. The main advantage of this approach (Fig, 1b) is that there is no need to evaluate and to model uncertainty sources. The main drawbacks of this approach are:

- The process of ‘extrapolation’ of output errors is not based upon fundamental principles: the concept of extrapolation of accuracy can not be demonstrated (however, proofs of validity can be supplied);

- The origin of uncertainty does not appear from the results: it is impossible to distinguish contributions to the output error bands.
- Range of application is limited by the database.

3. The CIAU Method

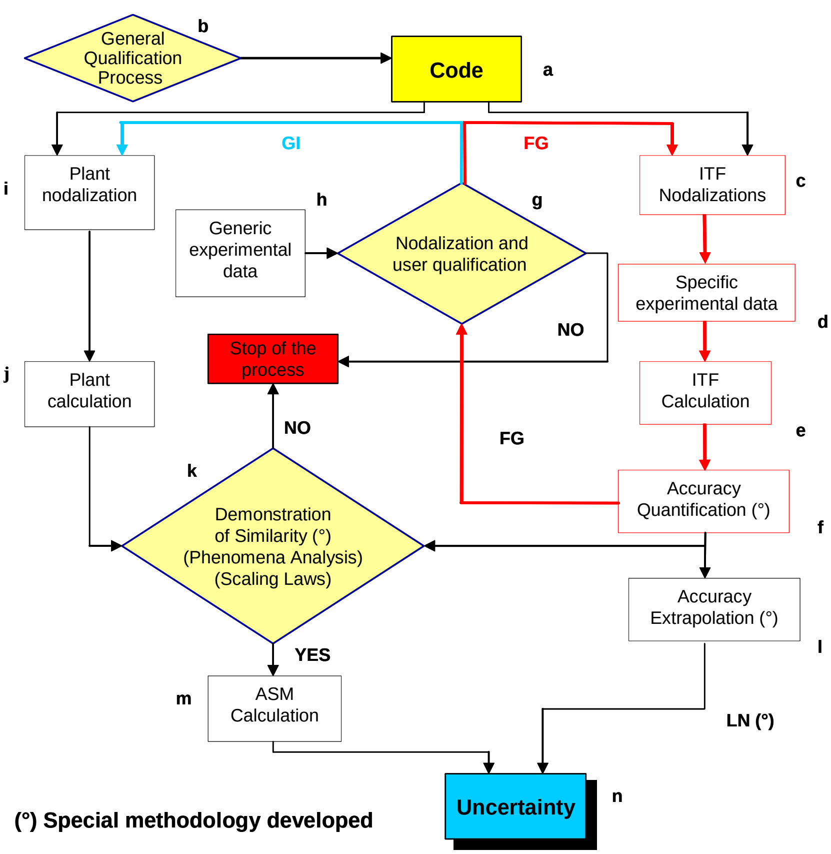
All of the uncertainty evaluation methods are affected by two main limitations:

- The resources needed for their application may be very demanding, ranging to up to several man-years;
- The achieved results may be strongly method/user dependent.

The last item should be considered together with the code-user effect, widely studied in the past, e.g. ref. [5], and may threaten the usefulness or the practical applicability of the results achieved by an uncertainty method. Therefore, the Internal Assessment of Uncertainty (IAU) was requested as the follow-up of an international conference jointly organized by OECD and US NRC and held in Annapolis in 1996. The CIAU method, refs. [6, 7], has been developed with the objective of reducing the above limitations. The basic idea of the CIAU can be summarized in two parts:

- Consideration of plant status: each status is characterized by the value of relevant quantities (i.e. a hypercube) and by the value of the time since the transient start.
- Association of an uncertainty to each plant status.

Figure 2: UMAE flow diagram (also adopted within the process of application of CIAU).



Assigned a point in the time domain, the accuracy in predicting the time of occurrence of any point is distinguished from the accuracy that characterizes the quantity value at that point. Time Accuracy (and Uncertainty) Vector, TAV & TUV, and Quantity Accuracy (and Uncertainty) Matrix, QAM & QUM, are derived. The overall accuracy (and uncertainty) is the geometric combination of the two accuracies (and uncertainties), i.e. time and quantity, in the two-dimensional space-time plane

Thus, the time-domain and the phase-space are distinguished. The time-domain is needed to characterize the system evolution (or the NPP accident scenario considering the framework of the derivation of the CIAU) and the phase-space domain is used to identify the hypercubes. Time and quantity accuracies are defined in the time-domain and in the phase-space hypercubes, respectively. Quantity and time accuracies can be assumed to derive by errors-in-code-models and uncertainties-in-boundary-and-initial-conditions including the time sequence of events and the geometric modelling (or nodalization) of the problem. In facts:

a) The 'transient-time-dependent' calculation by a code resembles a succession of steady-state values at each time step and is supported by the consideration that the code uses and is based on a number and a variety of empirical correlations valid (and qualified) at steady-state with assigned geometric discretization (or nodalization) for the concerned system. Therefore, quantity accuracy can be associated primarily with errors-in-code-models.
b) Error associated with the opening of a valve (e.g. time when the equivalent full flow area for the flow passage is attained) or inadequate nodalization induce time errors that cannot be associated to code model deficiencies. Therefore, time accuracy can be associated primarily with uncertainties-in-boundary-and-initial-conditions.

Summarizing, a hypercube and a time interval characterize a unique plant status to the aim of uncertainty evaluation. All plant statuses are characterized by a matrix of hypercubes and by a vector of time intervals. Each point of the curve (generic thermal-hydraulic code output plotted versus time) is affected by a quantity uncertainty and by a time uncertainty. Owing to the uncertainty, each point may take any value within the rectangle identified by the quantity and the time uncertainty. The value of uncertainty, corresponding to each edge of the rectangle, can be defined in probabilistic terms. This satisfies the requirement of a 95% probability level to be acceptable to the USNRC staff for comparison of BE predictions of postulated transients to the licensing limits in 10 CFR Part 50.

A simplified flow diagram of the CIAU is given in Fig. 3, where two main parts can be seen: the former dealing with the *development* of the method and the latter with its *application*.

The *development* of the method implies the availability of qualified experimental data (block a in Fig. 3), of qualified system codes calculation results (block b), of postulated transients including the definition of plant status (block c) and the selection of variables in relation to which the uncertainty must be calculated (block e). The support of experimental data (block a) is considered mandatory, whatever is the qualification process. Qualified code results (block b) signify the run of qualified code in a qualified computer/compiler, by a qualified user using a qualified nodalization [3]. The qualification level of the code results is evaluated from a qualitative and a quantitative point of view, making use of the FFTBM. If the UMAE uncertainty methodology is used (bounded area in Fig. 3), relevant experimental data and code calculation results (blocks a and b) are compared. Accuracy is evaluated qualitatively and quantitatively, block d. If accuracy is acceptable, block d, the Quantity Accuracy Matrix (QAM) and the Time Accuracy Vector (TAV) are generated, blocks f and g, respectively.

Now, the various plant statuses identified under block c can be filled by data coming from block b or from blocks f and g in the case of UMAE. The scenario independence check (block

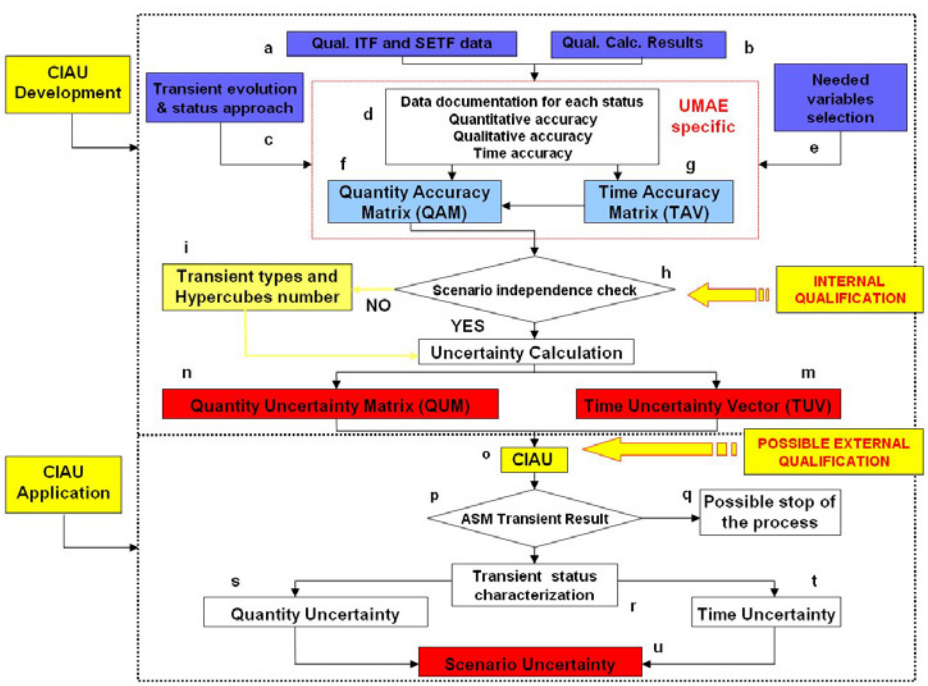
h) needs to verify that the transient type does not affect calculated uncertainties in each hypercube. For instance, it might happen that data from the analysis of several SBLOCA produce uncertainty values much higher than data from the analysis of a similar number of LBLOCA, when the same hypercubes are concerned. In this case, the outlet "NO" from the block h brings into the block i. The number of hypercubes, i.e. the ranges of variation of the driving quantities, must be changed or the transient type must be identified inside each hypercube. If the scenario independence check is positively passed, uncertainty values can be meaningfully assigned to each plant status. The already mentioned QUM and TUV are generated.

The *application* of the CIAU is straightforward once QUM and TUV are available. The 'error matrices' and the 'error vector' are currently used as a post-processor of a CIAU calculation. The ASM (Analytical Simulation Model), i.e. a qualified NPP nodalization in the UMAE nomenclature, is used to get the transient scenario. Once a generic event is predicted, block p, the six driving quantities are used to identify the succession of hypercubes. The time intervals are also identified by the predicted event time, block r. This leads to the quantity uncertainty and the time uncertainty values, blocks s and t, respectively, that can be combined to get the searched uncertainty bands. It may be noted again that uncertainty bands only envelope the quantities selected under block e. The computer tool UBEP is used to combine time and quantity uncertainty at each time of the predicted event, block u. Continuous uncertainty bands are generated and envelope the ASM calculation results.

4. Key Applications of the CIAU Methodology

Two main applications of the CIAU methodology with relevance to the nuclear industry are presented hereafter. More details may be found in Refs 8 and 9.

Figure 3: Simplified flow diagram of the CIAU.



4.1 Uncertainty analysis of the LBLOCA-DBA of the Angra-2 PWR NPP

Angra-2 is a 4 loop 3765 Mwth PWR designed by Siemens KWU. The NPP is owned and operated by the ETN utility in Brazil. The NPP design was ready in the '80s, while the operation start occurred in the year 2000 following about ten-year stop of the construction. The innovation proposed to the licensing process by the applicant consists in the use of a Best Estimate tool and methodology to demonstrate the compliance of the NPP safety performance with applicable acceptance criteria set forth in the Brazilian nuclear rule.

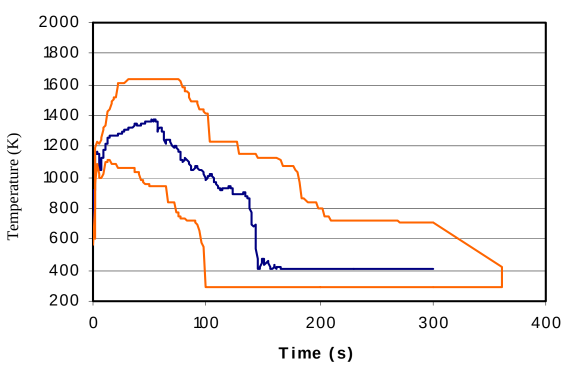
In this study [8], the CIAU application aimed at performing an 'independent' best-estimate plus uncertainty analysis of the LBLOCA-DBA of the Angra-2 PWR NPP. The analysis is classified as 'independent' in the sense that it was carried out by computational tools (code and uncertainty method) different from those utilized by the applicant utility.

The main results are summarized in Fig. 4a and 4b, where PCT and related uncertainty bands obtained by the CIAU and by the computational tools adopted by applicant, are given. The following comments apply:

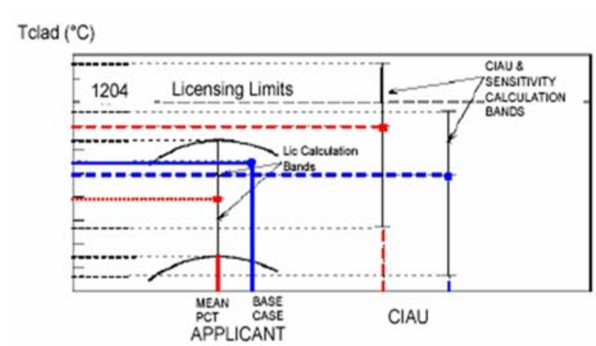
- Continuous uncertainty bands have been obtained by CIAU related to rod surface temperature (Fig. 4a), pressure and mass inventory in primary system. Only point values for PCT are considered in Fig. 4b.
- The CIAU (and the applicant) analysis has been carried out as best-estimate analysis: however, current rules for such analysis might not be free of undue conservatism and the use of peak factors for linear power is the most visible example.
- The conservatism included in the reference input deck constitutes the main reason for getting the 'PCT licensing' from the CIAU application above the acceptability limit of 1200 °C.
- The amplitude of the uncertainty bands is quite similar from CIAU and applicant. Discrepancies in the evaluation of 'PCT licensing' outcome from the way of considering the 'center' of the uncertainty bands. In the case of CIAU, the 'center' of the uncertainty bands is represented by the phenomenological result for PCT obtained by the reference calculation (1100 °C in Fig. 4a). In the case of applicant (Fig. 4b) the 'center' of the uncertainty bands is a statistical value obtained from a process where the reference calculation has a role (796 °C).
- The results of the CIAU method are supported by a number of 'finalized' sensitivity studies as large as about 150 (i.e. about 150 LBLOCA calculation have been performed to confirm the CIAU uncertainty results).

Figure 4: Result of CIAU application to Angra-2 LBLOCA analysis

4a) Uncertainty bands for rod surface temperature at 'axial level 9' of the hot rod realistic.



4b) Uncertainty evaluation: final result from the CIAU study and comparison with results of the applicant.



- The reference best estimate PCT calculated by the applicant (result on the left of the Fig. 4b) plus the calculated uncertainty is lower than the allowed licensing limit of 1473 K.
- The reference best estimate PCT calculated by CIAU (central result in the Fig. 4b) is higher than the PCT ‘proposed’ by the applicant and the upper limit for the rod surface temperature even overpasses the allowed licensing limit of 1473 K thus triggering licensing issues.

4.2 Best estimate and uncertainty evaluation of LBLOCA 500 mm for Kozloduy-3

The analysis of the ‘LBLOCA 500 mm’ (DEGB in CL) transient behaviour of the Kozloduy unit 3 VVER 440/230 NPP (675 MWth) [9] was carried out by adopting the Relap5 code. The specific purposes of the analysis include the assessment of the results and the execution of an independent safety analysis supported by uncertainty evaluation. A BE transient prediction of the ‘LBLOCA 500 mm’ was performed. Evaluation of the uncertainty was performed by CIAU for the RPV upper plenum pressure, the mass inventory in primary system and the hot rod cladding temperature. Only the last parameter is shown in Fig. 5 together with the uncertainty bands. The most relevant result is the demonstration that the PCT in the concerned hot rod is below the licensing limit. In the same Fig. 5, bounding results from two conservative calculations (i.e. obtained by a BE code utilizing conservative input assumptions) are given: one is the conservative calculation (DC, ‘Driven’ conservatism in Fig. 5), the other is the conservative calculation performed by UNIPI (RC, ‘Rigorous’ conservatism). The following can be noted:

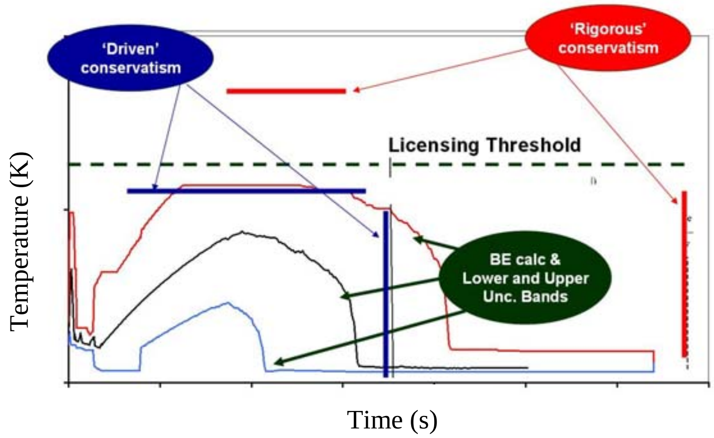
a) The conservative calculation DC is not “conservative” and does not bound entirely the BE plus uncertainty upper bound. This implies that code uncertainties are not properly accounted for by the adopted conservative input parameter values.
b) The conservative calculation performed by UNIPI [9] is correctly conservative, but its conservatism is such to cause PCT above the licensing limit. The comparison between the conservative PCT obtained by UNIPI and the upper bound of the calculation shows the importance to use a full BE approach with a suitable evaluation of uncertainty.

5. Extension to the Prediction of Uncertainty of 3D NK/TH Calculations: CIAU-TN

The successful applications of the CIAU methodology and the present trend to increase the use of best-estimate codes in 3D Thermal-hydraulic/Neutronics coupled calculations have addressed the further development of the CIAU methodology towards the introduction of the capability to predict the uncertainty in core power and in its spatial distribution as a function of time. This effort to implement the IAU capability into above mentioned system codes, constitutes a pioneering activity whose result is the CIAU-TN computer program that realizes the coupling between the UMAE uncertainty methodology and the RELAP5/PARCS coupled code [7]. Notwithstanding the full implementation and use of the procedure requires a database of errors not available at the moment, the obtained results give an idea of the errors expected from the application of present computational tool to problems of practical interest.

CIAU-TN is based upon the same idea of the original CIAU. The status approach implies the selection of new ‘driving’ quantities to take into account the thermal-hydraulics/neutron kinetics feedbacks between the two codes and to characterize the regions of the phase-space (hypercubes) to which assign the uncertainty values. In order to achieve this extension, the number of quantities (to select the NPP status) has been increased by two units. The application of CIAU-TN is straightforward once the uncertainty database is available: each time the transient enters in one plant status, uncertainty values are picked up from the database and

Figure 5: BE 500 mm LBLOCA analysis for Kozloduy Unit 3 NPP and uncertainty evaluation.



continuous uncertainty bands are automatically generated and superimposed to the selected quantities. The description of the CIAU-TN tool is beyond the scope of this paper and can be found in detail in Ref. [7]. The development and the assessment of the CIAU-TN for the uncertainty evaluation in coupled codes have been performed using the Peach Bottom 2 Turbine Trip (PBTT2) benchmark as a test demonstration problem [10]. The results have to be considered preliminary because, for a successful application of the methodology, a sufficiently large database has to be acquired to make the statistical evaluation reliable. At the present, this point of development can not be considered reached for CIAU-TN. Figure 6 shows the results of the CIAU-TN application to the analysis of PBTT2 performed by University of Pisa (UPI) [11] using RELAP5/PARCS coupled-code. Upper and lower limits have been predicted for the core power history (Fig. 6a), axial peaking factors distribution (Fig. 6b) and average radial peaking factors distribution (Fig. 6c).

6. Conclusions

The use of best-estimate codes within the reactor technology, either for design or safety purposes, implies understanding and accepting the limitations and the deficiencies of those codes. Therefore, uncertainty statements must supplement the application of best-estimate codes. A method to calculate the uncertainty associated with NPP computer code calculations directly integrated in the code has been briefly presented. CIAU and CIAU-TN constitute powerful tools that are originated by the combination of a qualified best-estimate system code and a suitable uncertainty methodology. The implementation of the CIAU and CIAU-TN capability allows the achievement of error (uncertainty) bands coupled with the results of the concerned system code calculation. The main advantage of an IAU approach consists in avoiding, from the methodology user point of view, to interpret logical statements that are part of the application process for all current uncertainty methods, i.e. avoiding user effect when using uncertainty methodologies. The above consideration does not exclude the use of engineering judgment: rather, engineering judgment is embedded into the development of the IAU method and it is not needed in its application. Key applications of CIAU and CIAU-TN have been presented to demonstrate the maturity level reached by the methods.

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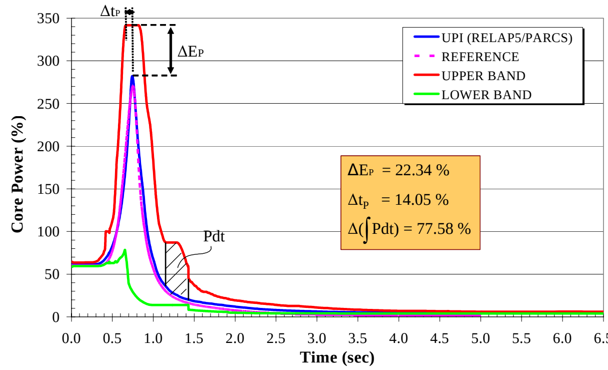
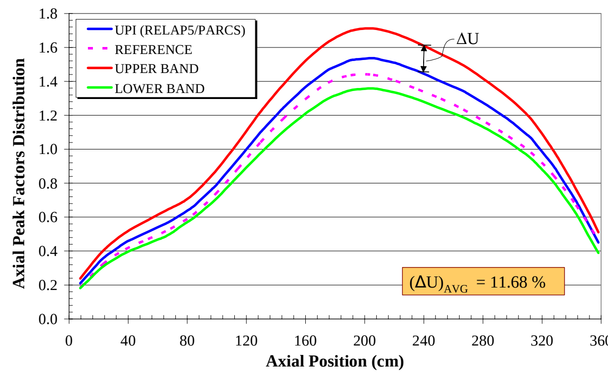
Figure 6: CIAU-TN application to the analysis of PBTT2: uncertainty bands.

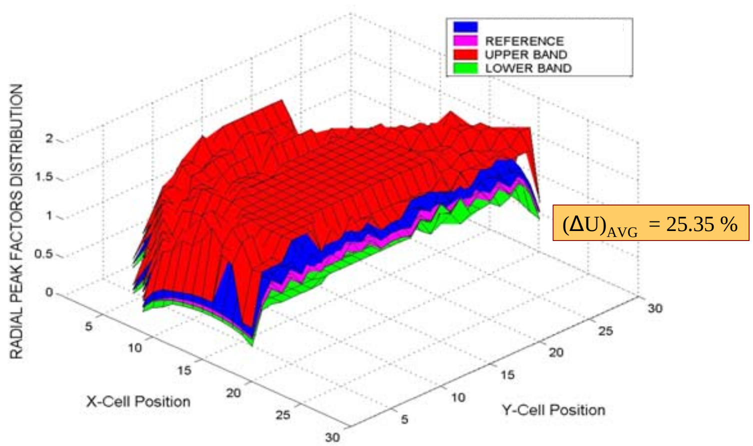
a) Core power history with uncertainty bands.



b) Axial peaking factors distribution at core power peak.



c) Radial peaking factors distribution at core power peak.



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